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# A Kaon Physics Program at the Fermilab Main Injector

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# A Kaon Physics Program at the Fermilab Main Injector

## 1 Introduction

Kaon decays have provided and will continue to provide an important window into our understanding of elementary particle physics and its current description, the Standard Model. The exploitation of precision measurements of kaon decay properties and measurements of rare, Standard Model allowed processes give some of the most stringent tests of the Standard Model and some of the best determinations of its parameters. Searches for extremely rare kaon decay modes forbidden in the Standard Model are one of the most fertile grounds in the quest for physics beyond the Standard Model. The list of physics topics under active investigation in the kaon sector include many of today's most important topics: the origin of CP violation, the accurate determination of the remaining unmeasured parameters of the Cabibbo, Kobayashi, Maskawa mixing matrix, the search for lepton number violation; to give a partial list.

Progress in kaon physics has been fueled by kaon beam sources of ever increasing intensity and quality in terms of purity and freedom from backgrounds. As the requirements for precision measurements and the need to control backgrounds in the study of rare processes increased, demands on the performance of kaon detectors have also grown greatly. Major progress has required beyond state of the art detectors to be conceived, designed and constructed in as high a kaon beam flux as possible.

The Fermilab Main Injector has the potential at its turn-on to become an outstanding source of high-intensity charged and neutral kaon beams for rare K decay experiments. Anticipated improvements in the intensity of the 120 GeV/c Main Injector proton beam over the first decade of operation should allow increased kaon fluxes of at least an order of magnitude above the initial kaon fluxes. Given a set of experiments capable of exploiting those intensities there is no reason to foresee anything but continued physics progress in this sector for a kaon physics program at the Fermilab Main Injector.

Fermilab has demonstrated with the KTeV detector, the CDF and D0 collider detectors, their upgrades, and others, the ability to regularly conceive, design, construct and commission beyond state of the art detector systems which achieve or exceed their physics design goals and extract superb physics analyses from the resulting data.

The most critical components of a successful experimental program at this level of difficultly are teams of physicists both knowledgeable and capable of mastering the difficulties of experiments where $10^{-7}$ branching ratio modes are used for online calibrations. Fermilab has a long tradition of precision experiments in kaons, hyperons and neutrinos dating back decades and more recently with the precision work of the Fermilab collider program in the vector boson and B meson sectors. Those original research groups are largely still intact with more than a generation of physicists trained in these techniques. KTeV is the most prominent example.

In the coming decade the energy frontier in elementary particle physics will again migrate from Fermilab back to the European Center for Nuclear Research, CERN, in Geneva Switzerland with the commissioning of the Large Hadron Collider (LHC). There are now, and have always been, at least three frontiers in particle physics; the highest energy, the highest measurement precision and the highest sensitivity to rare phenomena. The Fermilab experimental program will, of necessity, reemphasize these last two approaches to the research frontier in neutrino physics, kaon physics, top physics and elsewhere in the coming decade.

In this paper we describe a triad of kaon experiments which will form the foundation of a kaon physics program at Fermilab in the Main Injector era. These three experiments; KAMI, CKM and CPT, span the range of experiment types discussed above. KAMI will use the existing neutral kaon beam and the KTeV detector as the basis of a search for the Standard Model ultra rare decay $K_L \rightarrow \pi^0 \nu \overline{\nu}$. The rate of this decay mode is by far the theoretically cleanest measurement of the Standard Model parameter responsible for CP violation. CKM will measure the analogous charged kaon decay mode. Together these two experiments will determine the Standard Model contribution to CP violation independent of the B meson sector. The Standard Model parameters controlling CP violation must be observed to be the same in the K and B meson sectors in order to confirm the Standard Model as the sole source of CP violation in nature. CPT is a hybrid beam experiment using a high purity $K^+$ beam to produce a pure $K_0$ beam in order to search for violation of CPT symmetry at a mass scale up to the Planck mass. CPT also will measure new CP violation parameters to test the Standard Model and search for rare $K_S$ decays.

The Fermilab infrastructure for such a physics program largely already exists. The Main Injector will be an existing accelerator by late 1998 with beam properties comparable to any of the previous "kaon factory" proposals. The KTeV detector and neutral kaon beamline are unsurpassed in the world and were originally designed to also operate with the 120 GeV Main Injector beam as KAMI. The Fermilab Meson laboratory was originally designed as an area for fixed target experiments using 200 GeV proton beams. The charged kaon beam experiments will naturally find a home there. Both charged kaon experiments, CKM and CPT, will share a new high purity RF separated charged kaon beam based on superconducting RF technology which will provide the highest intensity and purity charged kaon beam in the world.

Discussions have already begun for new machines which would bring the energy frontier back from CERN to Fermilab in the post LHC era. The proton sources of these machines could provide orders of magnitude increases in kaon fluxes beyond the Main Injector. The kaon physics program at Fermilab is more than two decades old and may well have several decades of future.

# 2 CP Violation in the Kaon Sector

The origin of the matter/antimatter asymmetry manifest in our world is of fundamental interest and remains outside the scope of the now "Standard Model" of particle interactions.

The theoretical structure of the Standard Model can accommodate matter/antimatter asymmetries, but the dynamical origin of these effects must reside at a level of understanding beyond the Standard Model. After 33 years of hard work since the original observation of these asymmetries in the neutral kaon system, we are now at the threshold of performing measurements of striking new asymmetry effects expected in the Standard Model. These effects are observed through "CP violation" in the mixing and decay amplitudes of K and B meson decays. The Standard Model predicts large CP violation effects in the decay amplitudes of rare B meson and very rare kaon decays. More importantly, the Standard Model predicts effects in the B and K systems with a common formalism, so that matter/anti-matter asymmetries observed in these two different systems must agree if the Standard Model is on the right track.

To date, CP violation has only been observed through the window of $K_0 \leftrightarrow \overline{K_0}$ oscillations. The effect is manifest as a difference in the rate of $K_0 \rightarrow \overline{K_0}$ and $\overline{K_0} \rightarrow K_0$ mixing. Experiments at Fermilab and CERN are now underway to study this difference in precise detail, with the possibility of extracting a signal for CP violation in the decay amplitude of $K \rightarrow 2\pi$ decays. An observation of CP violation in a decay amplitude (known as "Direct CP Violation") would be the first really new piece of information about CP violation since the original discovery 33 years ago and the first significant step towards understanding its origin. This would be of immense significance. The extraction of Standard Model parameters from the measurement of $K \rightarrow 2\pi$ decays are presently limited in precision by large uncertainties in the theoretical predictions for the magnitude of direct CP violation.

In contrast, the theoretical predictions for rare B decays are more reliable though some important questions await experimental verification. The theoretical predictions for the very rare K decays are thought to be completely under control with rate uncertainties $< 10\%$ for these processes. The reliability and magnitude of the predicted asymmetries in rare B and very rare K decays provide laboratories to quantitatively evaluate the fundamental CP violating parameters of the Standard Model which has stimulated an ambitious world-wide effort to measure these effects.

The very rare kaon decays of greatest interest are $K_L \rightarrow \pi^0 \nu \overline{\nu}$ and $K^+ \rightarrow \pi^+ \nu \overline{\nu}$. In the context of the Standard Model, measurement of these two branching fractions can determine the two fundamental CP violation parameters of the model. These two parameters are referred to as $\rho$ and $\eta$, where $\eta$ directly sets the scale of CP violation within the model. Likewise, measurements in the system of B meson decays can determine the $\rho$ and $\eta$ parameters uniquely. Comparison of $\rho$ and $\eta$ in the K and B systems provides a very powerful test of whether the three generation Standard Model can accommodate CP violation. The $K_L \rightarrow \pi^0 \nu \overline{\nu}$ and $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ processes are expected to occur with branching fractions at the $10^{-11}$ and $10^{-10}$ level, respectively. Measurement of these processes is extremely challenging due to the very low branching fractions and the presence of unmeasurable neutrinos in the final states. Experimental rare kaon decay programs that can meet these technical challenges demand instrumentation that is at or beyond state-of-the-art in the field. These high performance kaon beam and detector systems enable the precision study of less rare kaon decays that are of interest in their own right, as well as providing key performance milestones along the way.

# 3 KAMI - A Measurement of the process $K_L \to \pi^0 \nu\overline{\nu}$

The primary motivation for the KAMI program is to observe the decay $K_L \to \pi^0\nu\overline{\nu}$ and to measure its branching ratio. It is extraordinarily difficult to control all backgrounds in order to observe this mode cleanly. The only particles directly observable are the decay products of the $\pi^0$. Early attempts to detect this decay have relied on observation of the Dalitz decay mode of the $\pi^0$ to $e^+e^-\gamma$. The charged vertex from the $e^+e^-$ provides kinematical constraints which allow for simple reconstruction of the $\pi^0$ and effective rejection of backgrounds. The best published experimental limit to date ($5.8 \times 10^{-5}$, 90% CL) from Fermilab experiment E799-I employed this method effectively.

While the Dalitz decay provides additional kinematical constraints, there is a two order of magnitude loss in sensitivity relative to the $2\gamma$ decay mode of the $\pi^0$. In order to reach the Standard Model sensitivity, the $2\gamma$ mode will ultimately have to be employed. This is a considerable experimental challenge. The signature of this decay is exactly two photons with an invariant mass consistent with a $\pi^0$ and no activity elsewhere in the detector.

Based on Monte Carlo simulations, a single event sensitivity of $10^{-13}$ per year using the $2\gamma$ decay mode appears feasible. This would result in 20-30 events for $10^{20}$ protons incident on the kaon production target, based on Standard Model predictions for the branching ratio. Such a proton flux could be delivered in less than one year.

The real challenge is to accurately predict the background levels and understand how to minimize them. There are several potential background sources to the decay $K_L \to \pi^0\nu\overline{\nu}$ and there are two observable quantities available to reject these backgrounds:

1. The vertex determined from the two photon clusters, assuming the $\pi^0$ mass, which must reconstruct within the fiducial region of the detector; and

2. the transverse momentum ($P_t$) of the reconstructed $\pi^0$, which is typically greater than 160 MeV/c, recoiling against the large $P_t$ generally carried away by the two neutrinos.

To better understand the background levels which will ultimately confront any attempt to measure $K_L \to \pi^0\nu\overline{\nu}$ at KAMI, a special half-day of data was taken during KTeV's run in December of 1996. During this special run the beam geometry was modified in order to allow an accurate measurement of the transverse momentum ($P_t$) of the $\pi^0$. In order to minimize backgrounds the beam size was carefully selected to balance beam rate and improved $P_t$ resolution. From a preliminary analysis, KTeV has obtained an upper limit on the branching ratio of 1.8 x $10^{-6}$ at a 90% CL. This represents a factor of 30 improvement over the best existing limit, obtained by E799-I using the Dalitz decay mode of the $\pi^0$.

Figure 1 shows the $P_t$ distribution of candidate events after the final cuts. The observed $P_t$ distribution can be well reproduced by the background modes $K_L \to 2\gamma$ and $\Lambda \to n\pi^0$. For $P_t$ values above 160 MeV/c$^2$, one event still remains. This remaining event appears to be a neutron interacting in the KTeV detector. This type of background will be considerably less troublesome for KAMI because the neutral beam will pass through nothing but vacuum until just upstream of the CsI.

KTeV intends to extend this measurement even farther during an anticipated run in 1999. With the addition of some photon veto counters, a sensitivity of 1.0 x $10^{-9}$ is expected in 4 weeks of dedicated running using the same beam configuration as in 1996.

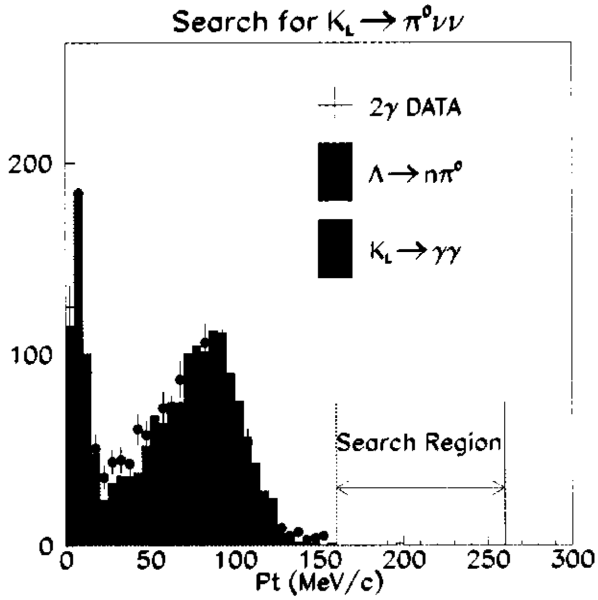


Figure 1: $P_t$ distribution of $K_L \to \pi^0\nu\overline{\nu}$ candidate events using the $2\gamma$ decay mode of the $\pi^0$ during a special 1 day run in December of 1996.

In order to progress beyond the $10^{-9}$ sensitivity level it will be necessary to obtain considerably larger kaon fluxes and to significantly upgrade the photon veto capabilities of the detector while retaining the excellent calorimetry already deployed by KTeV.

The Main Injector will provide about two orders of magnitude more protons per hour than what is now currently available at Fermilab resulting in a significant increase in kaon flux. While the 120 GeV protons provided by the Main Injector are lower in energy then those currently provided by the TeVatron, they are still more energetic than those at other kaon facilities in the world. Higher energy affords many significant advantages including better calorimeter resolution and better vetoing efficiency.

The existing KTeV detector, currently operating at an exceptionally high level, represents a significant investment of time, manpower and \$18M of capital. The KTeV detector and beam were designed for 800 GeV but accommodations for 120 GeV operations were designed in from the beginning. It can evolve into a powerful detector for KAMI in an efficient and cost effective manor. A schematic of the proposed KAMI detector is shown in Figure 2.

The heart of the KTeV detector, and the future KAMI detector, is the pure CsI calorimeter. The CsI calorimeter and its associated electronics represents an investment of approximately \$10M and 5 years of detailed and dedicated hard work by a sizable team of physicists, engineers and technicians. It is the most advanced, high-precision electromagnetic calorimeter currently in use. The energy resolution of the calorimeter is better than 1% over a range of 5-100 GeV. This level of performance will be essential for reducing backgrounds in KAMI.

A photon veto detector for KAMI will likely be based on the existing KTeV veto design. However, in order to improve the detection efficiency for low energy photons, finer sampling, more scintillation light and improved light collection geometry are required.

By making full use of the CsI calorimeter, along with a high-precision charged spectrom-

KAMI DETECTOR LAYOUT

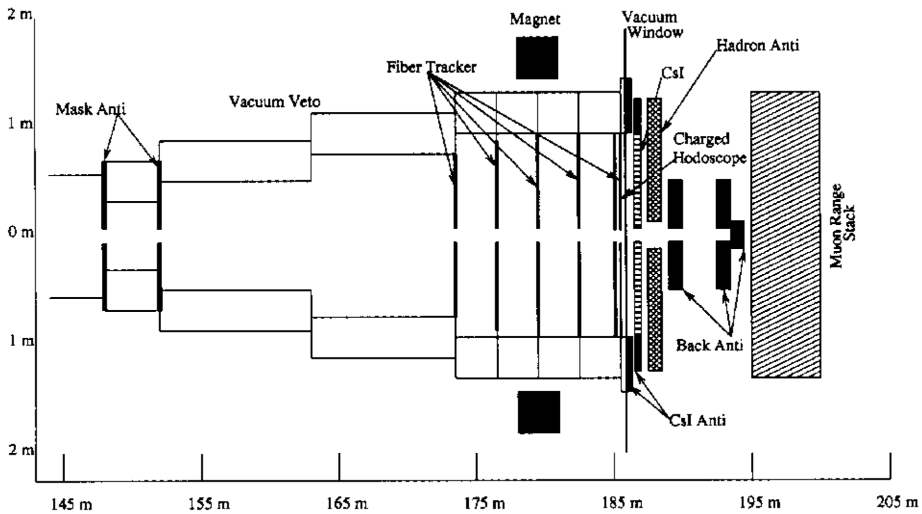


Figure 2: Schematic of the KAMI detector.

eter and photon vetos (sufficient for KTeV but not KAMI), the KTeV Collaboration has produced an impressive array of new results at this early date. These results include the first definitive observation of the CP violating decay $K_L \to \pi^+\pi^-e^+e^-$; the first observation of $\Xi^0 \to \Sigma^+e^-\overline{\nu}$ beta decay; and the previously described limit on $K_L \to \pi^0\nu\overline{\nu}$ using the $2\gamma$ decay mode of the $\pi^0$ for the first time.

Once the current KTeV run concludes and the group turns its full attention to data analysis, many more new and significant results will follow. Among the most important of these is the extremely difficult measurement of the Real part of $\epsilon'/\epsilon$. KTeV appears to have sufficient statistics and control of systematics to make this measurement with unprecedented precision.

Based on the performance of the KTeV detector, the new results already obtained and those certain to follow, and the experience which the neutral kaon group at Fermilab has for making difficult high-precision measurements we are optimistic that this program will lead to a precise measurement of the decay $K_L \to \pi^0\nu\overline{\nu}$ at the Main Injector.

In addition to $K_L \to \pi^0\nu\overline{\nu}$, there are other rare kaon decays which are sensitive to direct CP violation. According to the Standard Model, a substantial fraction of the decays $K_L \to \pi^0e^+e^-$ and $\pi^0\mu^+\mu^-$ should be direct CP violating and are expected to have branching ratios within reach of KAMI.

KAMI will also have the capacity to perform sensitive searches for a variety of other rare and forbidden decays. These include processes forbidden by the Standard Model, such as the lepton flavor violating decay $K_L \to \pi^0\mu^\pm e^\mp$. Other processes, such as $K_L \to \mu^+\mu^-e^+e^-$, are highly suppressed in the Standard Model and provide windows where new physics might be detected.

It will also be possible to extend the sensitivity of the $\epsilon'/\epsilon$ measurement at the Main Injector, should it be necessary. A statistical accuracy of $3 \times 10^{-5}$ is feasible at the Main Injector in 1 year of running based on the order of magnitude increase in decay rates combined with the 7 fold increase in the regeneration amplitude obtained with the lower kaon momentum.

# 4 CKM - A Measurement of the process $K^+ \to \pi^+\nu\overline{\nu}$

Measurements of rare charged kaon decays have historically relied on two methods; "in-flight" and "stopped kaon" techniques. In-flight experiments measure kaon decays from a well prepared intense beam of high energy kaons. Stopped-kaon experiments measure decays from an intense low energy beam of kaons that have been stopped in material so that the kaons are decaying at rest. The current state of the art detector searching for $K^+ \to \pi^+\nu\overline{\nu}$ decays is now running at Brookhaven National Laboratory (Experiment E787) using the stopped-kaon technique. The Brookhaven collaboration has steadily developed the stopped-kaon technique over the last 15 years to the point where the experiment now has an expected sensitivity of observing a few events at the Standard Model branching fraction level of $1.0\times10^{-10}$. The evolution of the Brookhaven experiment has been quite impressive, particularly in light of the fact that at their outset 15 years ago this process was only probed at the $10^{-6}$ level and the possible theoretical range extended upwards to the $10^{-9}$ level. Despite the steady progress of the Brookhaven experiment, it is unclear how the stopped kaon technique can be pushed beyond a single event branching ratio sensitivity of perhaps $10^{-11}$.

The expected theoretical uncertainty in the $K^+ \to \pi^+\nu\overline{\nu}$ branching fraction is 5-10%, which motivates a quantitative experiment to measure the process to at least this level of precision. This target level of precision requires an experiment capable of observing 100 events over a relatively small background. In order to achieve this level of sensitivity in a timely way it is clear that a kaon decay rate considerably higher than 1 MHz is required. High decay rates (5-10 MHz) in turn require detector systems that can respond and recover on the time scale of 10's of nanoseconds rather than microseconds. In an effort to realize this level of sensitivity a collaboration has recently formed that is seriously investigating a 100-event measurement using the in-flight technique. The in-flight technique is attractive because of the possibility of using intrinsically fast (i,e, few nanosecond time scale) detectors. In contrast the stopped kaon technique relies for particle identification on observing the full $\pi^+ \to \mu^+ \to e^+$ decay chain for which the time scale is dominated by the $\mu$ lifetime. The higher $K^+$ beam energy produces daughter particles with much higher energy which facilitates clear measurement of their properties.

The in-flight collaboration is designing an experiment for the Fermilab Main Injector, (<u>*C*</u>harged <u>*K*</u>aons at the <u>*M*</u>ain injector, CKM) where the 120 GeV fixed target proton beams can be exploited as a source for very intense secondary $K^+$ beams. The large flux and high energy of the generated $K^+$ beams are both crucial to the CKM in-flight measurement strategy. A successful 100-event measurement of $K^+ \to \pi^+\nu\overline{\nu}$ must limit backgrounds to less than the $10^{-11}$ level. At this extraordinarily low level, background sources arise through detector mismeasurements of relatively common $K^+$ decays and beam interactions with materials that compose the detector. The background problem is further exacerbated by the fact that kinematic information of only one $\pi^+$ of the three decay particles is measurable. The CKM experiment addresses these background issues by measuring all of the kinematic information of the incident $K^+$ and decay $\pi^+$ with two redundant and orthogonal detector

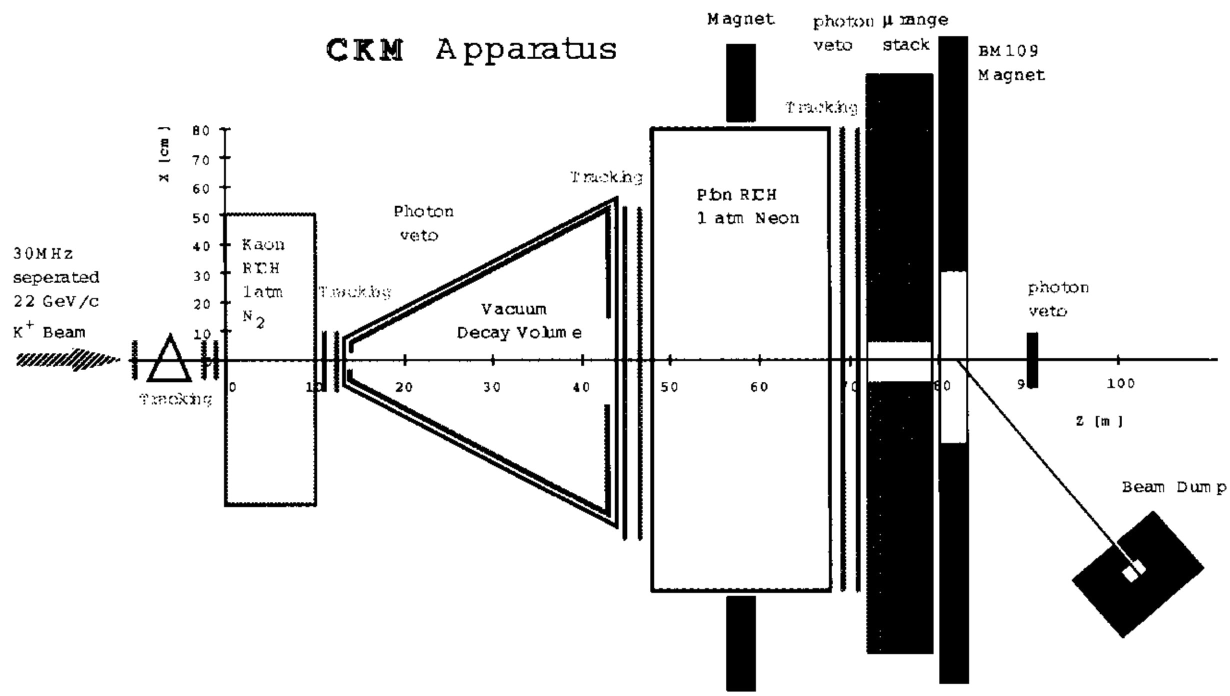


Figure 3: Schematic of the CKM detector.

systems. It is critical that the detector systems cross-check each other, and that the inevitable mismeasurement vulnerabilities of the two redundant systems be different. It is essential that the redundant detector systems present a minimum of material to the traversing beam particles, so that detector rates are dominated by $K^+$ decays rather than interactions.

The CKM detector as shown in Figure 3 is a novel hybrid of a conventional high-rate momentum spectrometer and a "velocity spectrometer". The momentum spectrometer magnetically analyzes the momentum vectors of the incident $K^+$ and the decay $\pi^+$ with high rate tracking stations on either side of the analysis magnets. The velocity spectrometer measures the velocity vectors of the incident $K^+$ and decay $\pi^+$ with photomultiplier tube based Ring Imaging CHerenkov (RICH) counters. Simultaneous measurement of the velocity and momentum allow the incident and decay charged particles to be identified as kaons, pions, muons or electrons. The kaon decay volume is hermetically lined with photon veto detectors that are crucial in tagging background processes from primarily $K^+ \to \pi^+\pi^0$ decays which are kinematically similar to $K^+ \to \pi^+\nu\overline{\nu}$ but occur at rate that is $10^9$ times as great! Likewise, background from the copious $K^+ \to \mu^+\nu$ process where the muon is misidentified as a pion must be controlled to less than the $10^{-11}$ level. This misidentification background is controlled with redundant muon identification of the RICH system and the muon detector system at the downstream of the CKM detector.

The beam incident on the CKM detector has a tightly defined momentum of (22 +/- 0.2) GeV/c. The kaon purity of the beam is dramatically enhanced with the use of RF separation techniques that separate the kaons away from the copious pions and protons in the beam. This separated beam minimizes the rate of spurious charged particles in the detector, which is crucial given the already high rate of kaon decays that are challenging the rate capability of the apparatus. Development of this state-of-the-art separated beam is stimulating a great deal of interest in the accelerator and beam physics community. It is clear that the technology required for this beamline has direct relevance for next generation accelerator concepts that will define the future of high energy physics.

Detailed studies of the feasibility of an in-flight experiment based on the CKM concept are now just beginning. Early cost estimates of the CKM detector and separated beam are 12M and 3M dollars respectively. The relatively high energy and purity of kaons produced by the Fermilab Main Injector are absolutely crucial to the redundant detector strategies being studied for the CKM apparatus. The most novel element of the CKM detector is the velocity spectrometer. A velocity spectrometer of similar scope to CKM is successfully operating now in the Fermilab SELEX experiment and the demonstrated analysis power of that device is an exciting milestone for CKM. Likewise, the separated $K^+$ beam is critical to the success of CKM, and significant R&D on this challenging accelerator and beamline technology is now starting at Fermilab. Experiments that define the frontier of rare kaon decay physics are well represented in the CKM design group. The collaborators designing the CKM apparatus are all veterans of rare kaon decay experiments at Brookhaven and Fermilab, and are cautiously optimistic that the beam and detector techniques pursued by CKM will lead to a precise measurement of $K^+ \to \pi^+\nu\overline{\nu}$ in the next decade.

# 5 CPT - A Search for CPT Violation in $K^0$ Decay

The CPT experiment will exploit the unique features of the main injector accelerator for an ambitious program of kaon physics complementary to the KAMI and CKM experiments. This experiment will test CPT symmetry conservation with sensitivity at the Planck scale, measure CP violation parameters to test the Standard Model in new ways, and search for rare decays of the $K_S$ meson.

All quantum field theories (including the Standard Model of the elementary particles) assume CPT symmetry invariance. But there is a theoretical hint of the level at which CPT symmetry might be violated. This comes from the fact that the CPT theorem is not valid in general relativity, and quantum gravity effects may violate CPT symmetry. One expects to see these effects at the Planck scale, at energies of $M_{Planck}c^2 = \sqrt{\hbar c^5/G} = 1.2 \times 10^{19}$ GeV.

The most sensitive test of CPT conservation comes from a measurement of the phase of the CP violation parameter $\eta_{+-}$, and a comparison of this phase to the phase of $\epsilon$. A CPT violating mass difference between the $K^0$ and $\overline{K}^0$ mesons would generate a phase difference between $\eta_{+-}$ and $\epsilon$. In the formula which connects this mass difference to this phase difference, Nature has been kind: a factor of about $10^{-17}$ appears that allows a modestly accurate measurement of the phase difference to test very accurately whether there is a $K^0 - \overline{K}^0$ mass difference. The most sensitive experimental measurement of this phase difference came from Fermilab experiment E773, which measured the phase difference to about 1 degree accuracy, and placed an upper limit on the relative mass difference (at 90% confidence level) of $1.3 \times 10^{-18}$. This is 31 times the Planck scale prediction of $M_K/M_{Planck} = 4 \times 10^{-20}$. To reach the Planck scale one must measure the phase of $\eta_{+-}$ to an accuracy of 0.03 degrees.

This is not a simple task. The only way to measure the phase of $\eta_{+-}$ is to observe interference between $K_L$ and $K_S$ decays to the $\pi^+\pi^-$ final state. Therefore the experiment is designed to maximizes this interference. The calculated sensitivity of the proposed experiment will allow a measurement the phase of $\eta_{+-}$ with sufficient accuracy to reach the Planck scale.

In addition one must measure the phase of $\epsilon$. In the Standard Model this can be calculated very accurately, if certain decay parameters of the $K^0-\overline{K}^0$ system are known. Unfortunately, the present uncertainty in the phase of $\epsilon$ is 2.8 degrees. So to reach the Planck scale requires a set of subsidiary measurements: of x (the parameter characterizing violation of the $\Delta S = \Delta Q$ rule) and the two CP violation parameters for $K_S$ decays to three pions, $\eta_{+-0}$ and $\eta_{000}$. Calculations indicate that the proposed experiment will be able to make these measurements to sufficient accuracy.

Since the experiment is designed to have the largest $K_L - K_S$ interference possible, it will be used to measure several CP violation parameters much better than they are currently known, and perform tests of the Standard Model that have never been made before. All CP violation seen to date has been in decays of the $K_L$ meson. These measurements of $\eta_{+-0}$ and $\eta_{000}$ will be the first observation of CP violation outside the $K_L$ system. The Standard Model predicts that direct CP violation will be a large effect, up to 10% here; and there are predictions of effects beyond the Standard Model (from theories with right-handed intermediate bosons for example) that could make $\eta_{+-0}$ and $\eta_{000}$ be 50% larger than the expected values. These are important tests of the model.

The CP violation parameter in $K_L \to \pi^+\pi^-\gamma$ decays will be measured much better than it is currently known. In this decay the contribution of direct CP violation is relatively large, about 1%. The detailed comparison of $\pi^+\pi^-$ and $\pi^+\pi^-\gamma$ decays will search for this important effect. This study will result in a measurement of the CP violation parameter $\eta_{+-}$ an order of magnitude more accurate than present. This will make possible an additional CPT symmetry conservation test using the Bell-Steinberger relation.

A great deal of attention has been paid to searches for rare decays of the $K_L$ meson, but little work has been done on the $K_S$. Some of the interesting $K_S$ searches are for decays that test strangeness-changing neutral currents. One such decay is $K_S \to \pi^0 e^+ e^-$. This is a rare but CP conserving decay. Its branching ratio is needed in order to unambiguously disentangle the indirect CP violating contribution to $K_L \to \pi^0 e^+ e^-$ decay.

The $K_L/K_S$ system forms a finely balanced interferometer that can be affected by small perturbations like CP violation and CPT violation (if it exists). This experiment is designed to maximize this interference to study these effects. It consists of an RF-separated $K^+$ beam that strikes a target at the entrance of a magnetized collimator (called a hyperon magnet) which defines a short neutral beam originating from the target. Neutral kaons are copiously produced by charge exchange with a very small anti-kaon component. Since the interference from $K^0$'s has the opposite sign from that of $\overline{K}^0$'s, this maximizes the interference between the $K_L$ and $K_S$ decays of the K mesons in the beam (the counterexample would be a 50/50 mixture of $K^0$'s and $\overline{K}^0$'s which would show no net interference). The detector is a spectrometer consisting of drift chambers and an analysis magnet, a lead glass electromagnetic calorimeter, and muon detectors as shown in Figure 4. It is planned to use previously existing detector apparatus whenever possible, and estimate that the detector cost would be about $2,500k.

A critical experimental issue is the need for a pure $K^+$ beam. Building such a beam

The CPT Experiment

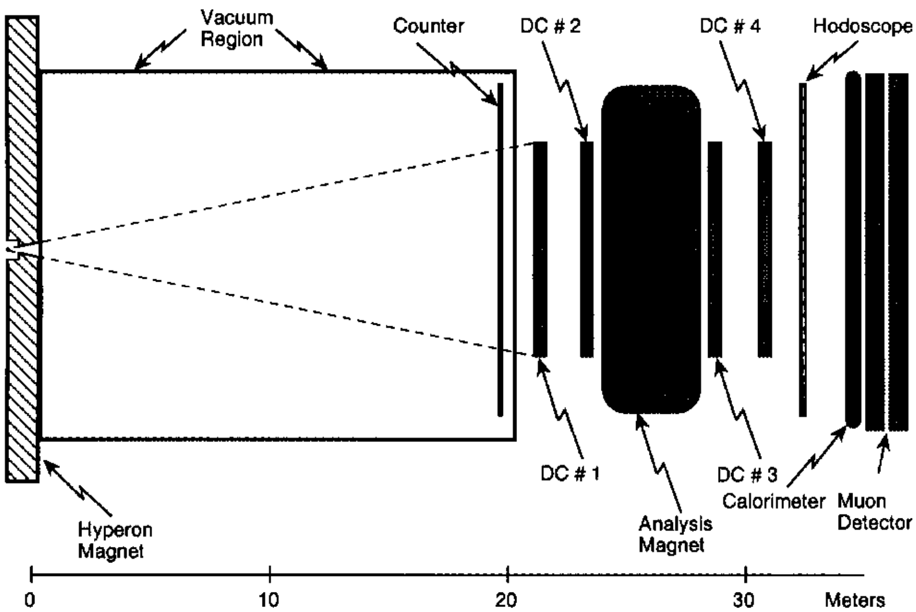


Figure 4: Schematic of the CPT detector.

requires solving two main problems: designing the optics of the beam to accomplish the separation, and building the necessary RF cavities. It should be noted that two experiments (CPT and CKM), would use this beam, thus providing a great saving to the cost of both experiments. Kaon fluxes of order $10^8$ $K^+$/spill at a momentum near 22 GeV/c with a non-kaon impurity of less than 10 percent is required. We have made a design that accomplishes all of the $K^+$ beam goals for the two experiments and uses $5{\times}10^{12}$ protons per spill from the new Main Injector Accelerator at FNAL.

The RF cavities for the separated K+ beam must be superconducting, since the Main Injector spill length would require enormous RF power otherwise. C-band frequency (5.79 GHz) RF cavities were used in the only superconducting RF separated beam previously built; at CERN in 1977 were a deflecting field of 1.3 MV/m was achieved. The state of the art has advanced since that time, and it is conceivable that the required 8MV/m can be achieved with a modest R&D effort. Initial R&D costs are estimated at $750k, with a total cavity fabrication cost of $1800k. The time scale for this work is reasonably matched to the Main Injector schedule, and the costs are reasonable for a facility that would initially serve two experiments and perhaps others in the future. This beam could also be modified for antiprotons for example. Suitable real estate exists in the Meson area that could house the target pile, beam line elements, and both experimental detectors.

The Main Injector era will be the first time that it is possible to build a high energy pure $K^+$ beam that can be employed to drive a tertiary beam of pure $K^0$ mesons. The CPT experiment seeks to exploit this possibility to do an experiment with the largest possible interference between $K_S$ and $K_L$ mesons. The collaboration includes physicists with a significant previous experience in type of $K_S^0$ physics. CPT symmetry conservation will be tested with sensitivity at the Planck scale, measure new CP violation parameters to test the

Standard Model, test the $\Delta S = \Delta Q$ rule, and search for rare $K_S^0$ decays.

# 6 Fermilab Facilities for Kaon Experiments

Fermilab is currently preparing the plans to mount the next generation of its kaon program. Recently a conceptual design on the conversion of the 800 GeV Switchyard and Experimental Areas for use in a smaller 120 GeV program was completed. The plan takes advantage of much existing equipment from the nearly completed Tevatron Fixed Target program. The Meson Lab was originally designed for use at 200GeV–its reconversion to lower energy from 800 GeV is straightforward. It would provide a fine site for a few experiments and test beams using charged kaons, pions and protons. The new construction for the KTeV experiment was done with the Main Injector in mind all along. Conversion is straightforward there as well .

There are several areas where the three experiment's technical requirements have strong overlaps with each other and with other technical developments at Fermilab. CKM and CPT will share both the development and use of the separated beam. KAMI and CKM have similar needs and requirements from photon veto systems. KAMI is planning to use a scintillating fiber tracker built with technology now under development by Dzero. These synergies should provide time and cost savings to each of these projects.

Detailed designs and critical R&D efforts will be completed during the next two years on each of these experiments. Upgrades and new detector construction would begin in 2001. The program will be smaller than the 800 GeV program, but will still have the breadth to concentrate on precise tests of the Standard Model from several fronts. CP violation studies and unitarity tests using kaons will produce results just around the time that B Factory results are expected.

# 7 Present Status of the Fermilab Main Injector Kaon Physics Program

The three experiments discussed above have begun the process of approval as Fermilab experiments. An approval of a proposal at Fermilab implies a commitment of the full faith, credit and budget of the laboratory in support of the experiment. The CKM experiment was submitted as a expression of interest and publically presented to the Fermilab program advisory committee (PAC) in April 1996. The CPT experiment was submitted as a letter of intent in October 1996. KAMI submitted a letter of intent in 1991 and is presently preparing an updated submission to the laboratory.

A "Workshop on Fixed Target Physics at the Fermilab Main Injector" held at Fermilab on May 1-4, 1997 was attended by more than 200 physicists. The kaon physics program was a major activity in this workshop with nearly half the physicists participating in one or more of the three working groups corresponding to the KAMI, CKM and CPT experiments. An outcome of this workshop was increased activity on each of the three experiments. Each group now has about 10 physicists meeting regularly to advance each of the experiments toward a full proposal. The Fermilab PAC had a presentation on the prospects for a kaon physics program with the Main Injector based upon the workshop summaries of kaon working groups. The PAC was supportive of the experiments with the recommendation "... that the proponents continue design studies toward the preparation of proposals." Guidance from the Fermilab director indicates that "substantial funding for a [kaon] Main Injector experiment is unlikely to be available before FY2002."

The Fermilab Main Injector is nearly completed as a construction project with commissioning and first delivery of beam scheduled in 1998. The design to reconfigure the upstream areas of the beam switchyard are complete and this work will be completed in the coming year. Design work is already in progress for the modification to the existing beamline transport required to deliver 120 GeV Main Injector protons to the Meson laboratory and KTeV detector hall. Some of this work is planned for the Main Injector installation shutdown scheduled in FY98. Design work for the secondary kaon beamlines has begun as has R&D for the superconducting RF cavities required for the separated charged kaon beam and layouts of the beams in the Meson area. Some beam might be available for use by kaon experiments as early as the first full run of the Main Injector which begins in FY2000.

The kaon physics program at the Fermilab Main Injector is evolving well. Three groups have formed and are now designing experiments which will significantly advance the state of the experimental art of kaon physics and make important contributions to our understanding of particle physics at the level of the fundamental symmetries of nature and stringent tests of the Standard Model. These groups have as their principle assets decades of hands-on experience in kaon physics developed both at Fermilab and elsewhere. The experimental challenges in these experiments are formidable but the physics rewards for successful measurements more than justify the effort and costs. The adaptation of the Fermilab infrastructure to accommodate this program is relatively straightforward and cost effective given the large investment already committed to the Main Injector. These three experiments are the beginning of a program. There is every reason to believe that future new kaon experiments of sufficient interest and merit can be accommodated in the Fermilab program with similar ease.